Analysis and High-Resolution Modeling of Tropical Cyclogenesis during the TCS-08 and TPARC Field Campaign

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LONG-TERM GOAL

The long-term goal of this project is to improve the prediction of tropical cyclone (TC) genesis, structure and intensity changes through improved understanding of the fundamental mechanisms involved. The accurate prediction of TC genesis, structure and intensity changes is critical to Navy missions and civilian activities in coastal areas. Significant gains have been made in the TC track prediction over the past decades. The genesis and intensity forecast, however, has shown very little progress during the same period. A main factor contributing to the lack of skill in the prediction of TC genesis and intensity is the lack of observations prior to and during TC genesis and intensification periods and the inadequate understanding of physical mechanisms that control the cyclogenesis and intensity change. The TCS-08 and TPARC field campaign provide an unprecedented opportunity for us to gain the first-hand insight of observed characteristics of TC genesis in western Pacific and to compare them with high-resolution model simulations. By analyzing and assimilating these data, we intend to understand the physical mechanisms that involve the TC internal dynamic and thermodynamic processes, external forcing, and scale interactions. Only after thoroughly understanding these processes, can one be able to tackle the weaknesses in the current state-of-art weather forecast models.

OBJECTIVE

The objective of this project is to investigate the synoptic and climatic aspects of tropical cyclone (TC) genesis in the western North Pacific (WNP). On one hand, specific synoptic and dynamic processes through which an initial weak vortex (either mid-level or near-bottom vortex) develops into a TC will be investigated in a cloud-resolving model. On the other hand, the large-scale control of the Madden-Julian Oscillation (MJO) and El Nino-Southern Oscillation (ENSO) on TC genesis in the WNP will be examined. Additional effort is to conduct data assimilation using data collected from TCS-08

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observational campaign. We will examine how the cyclogenesis forecast may be significantly improved with a better description of the dynamic and thermodynamic precursor signals.

APPROACH

For understanding the synoptic and dynamic aspects of cyclogenesis, a multi-nested WRF model (with 2 km resolution in the innermost mesh) will be used to simulate both idealized and real-case cyclogenesis events. Through the diagnosis of the model outputs, we intend to understand the common and different development characteristics associated with cyclogenesis in an environment with a near bottom vortex (EBV) and an environment with a mid-level vortex (EMV). The genesis time for each model run will be defined based on an objective way. A concept of the cyclogenesis efficiency (which is related to the initial environmental dynamic and thermodynamic conditions) will be introduced. A number of idealized experiments will be designed to illustrate the relative importance of initial column-integrated absolute vorticity, PBL parameters, surface fluxes, and vertically integrated relative humidity in determining the TC genesis efficiency.

For understanding the climatic aspect of cyclogenesis, various statistical tools such as the wavenumber-frequency analysis, lagged regression analysis, and composite analysis methods will be applied to understand the role of the MJO and ENSO in determining the intraseasonal and interannual variability of TC activity in the WNP.

For the data assimilation task, WRF 3DVar assimilation system will be employed. Because the TCS-08 campaign provides variety types of in-situ data at irregular spatial and temporal intervals, we intend to construct a high-resolution regular-grid reanalysis product that combines in-situ observations (such as ELDORA radar, Doppler wind lidar, dropsondes and driftsondes) with satellite remote sensing products.

WORK COMPLETED

A paper related to mid-level and bottom vortex cyclogenesis efficiency was published in *Journal of Tropical Meteorology*. A book chapter entitled “Synoptic and climatic aspects of tropical cyclogenesis in western North Pacific” was published in a book named “*Cyclones: Formation, triggers and control” edited by K. Oouchi and H. Fudevasu.* Large-scale factors including the ENSO and MJO that affect multiple TC genesis in the WNP were investigated. A paper about the interannual variation of multiple TC events in the WNP was published in the *Advances in Atmospheric Sciences*. The bimodal feature of TC frequency in Bay of Bengal was investigated, and the result was published in *Journal of Climate*. A manuscript entitled “Characteristics of tropical cyclone genesis in the western North Pacific during the developing and decaying phases of two types of El Niño” was submitted to *J. Climate*, and is currently under review.

Precursor signals associated with TC genesis during 2008-2009 were investigated, using the high-resolution YOTC (Year of Tropical Convection) data. A draft manuscript is in a final stage, and will be submitted to a referred journal in near future.

RESULTS

1. Tropical cyclone genesis efficiency: mid-level versus bottom vortex

Cloud resolving Weather Research and Forecasting (WRF) model simulations are used to investigate tropical cyclone (TC) genesis efficiency in an environment with a near bottom vortex (EBV) and an environment with a mid-level vortex (EMV). Five sensitivity experiments were designed. In the first experiment (MID_VORTEX), we mimic a mid-level precursor condition, by specifying an initial cyclonic vortex that has maximum vorticity at 600 hPa. The horizontal structure of this mid-level vortex has a maximum wind speed of 8 m s^{-1} at a radius of 100 km and a size of 500 km radius (where the wind vanishes). The vorticity gradually decreases both upward and downward, and vanishes at the surface. In the second experiment (BTM_VORTEX), an initial maximum precursor perturbation with a maximum wind speed of 8 ms^{-1} is located at the surface. In the third experiment (SHAL_MID), the initial vortex is similar to MID_VORTEX except with a shallower mid-level vortex so that the wind vanishes below 800hPa. In the fourth experiment (SHAL_BTM), the initial vortex is similar to BTM_VORTEX except that it is mainly confined below 800hPa. In the fifth experiment (MOIST), the initial vortex is similar to BTM_VORTEX except with higher initial relative humidity.

The sensitivity experiments show that the genesis timing depends greatly on initial vorticity vertical profiles. The larger initial column integrated absolute vorticity, the greater the genesis efficiency is. For given the same column integrated absolute vorticity, a bottom vortex has higher genesis efficiency than a mid-level vortex.

A common feature among these experiments is the formation of a mid-level vorticity maximum prior to TC genesis irrespective where the initial vorticity maximum locates. Both the EMV and EBV scenarios share the following development characteristics: 1) a transition from non-organized cumulus-scale (~5 km) convective cells into an organized meso-vortex-scale (~50-100 km) system through upscale cascade processes, 2) the establishment of a nearly saturated air column prior to a rapid drop of the central minimum pressure, and 3) a multiple convective-stratiform phase transition.

A genesis efficiency index (GEI) is formulated that include the following factors: initial column integrated absolute vorticity, vorticity at top of the boundary layer and vertically integrated relative humidity. The calculated GEI reflects well the simulated genesis efficiency, and thus may be used to estimate how fast a tropical disturbance develops into a TC.

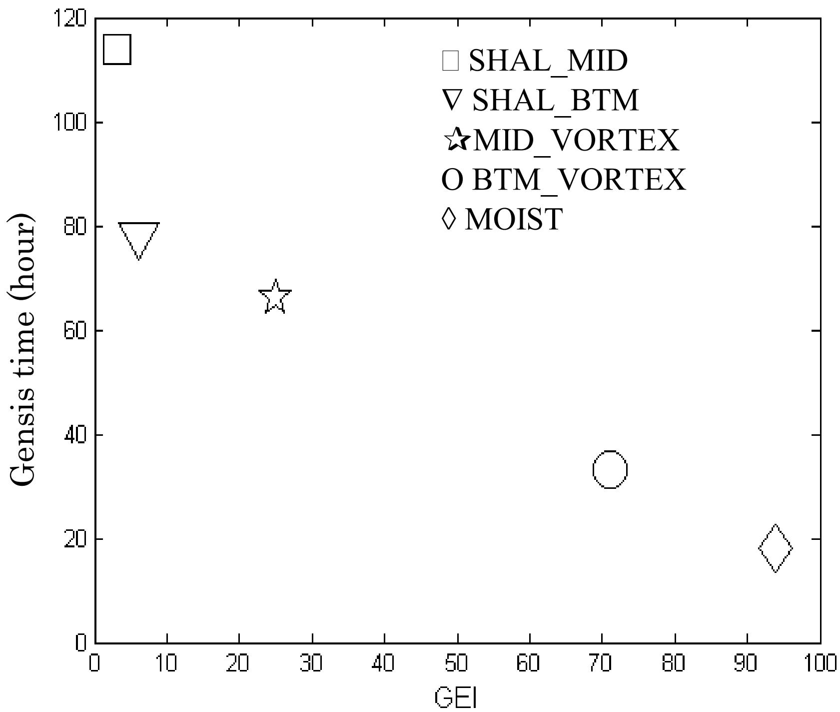

Fig. 1 The diagram shows the relationship of GEI to the genesis timing in the five experiments.

Figure 1 illustrates the relationship between the model genesis time and the calculated GEI. The index reflects well the impact of the initial environmental vorticity and moisture profiles on genesis efficiency. That is, a larger GEI corresponds to a faster genesis period. For instance, MOIST has the highest GEI and the shortest genesis period, indicating the important role of setup of a near-saturated air column in TC genesis. In SHAL_MID, the GEI is the smallest, corresponding to the slowest cyclone development. The GEI is greater in SHAL_BTM than in SHAL_MID, because the former attains greater PBL convergence even though it has slightly weaker initial column integrated absolute vorticity.

2. Bimodal character of cyclone climatology in Bay of Bengal

The annual cycle of tropical cyclone (TC) frequency over the Bay of Bengal (BoB) exhibits a notable bimodal character, different from a single peak in other basins. The monthly occurrence number of TCs based on JTWC best track data in seven major TC active regions is shown in Fig. 2. Consistent with previous studies, there is a marked difference in the TC genesis frequency between the BoB and other ocean basins. TC frequency in the BoB has two peaks in monsoon transition periods (April-May and October-November), while very low genesis frequency occurs during the strong southwest monsoon period (June-July-August-September).

Previous studies suggested that the bimodal feature of TC frequency in the BoB and AS is attributed to the annual cycle of the background vertical shear as strong vertical shear in boreal summer prevents TC formation. Here we will develop a quantitative diagnosis method to reveal the relative roles of large-scale environmental factors in causing the bimodal feature. Using the NCEP monthly reanalysis data

for 1981-2009, we calculate the box-averaged climatologic monthly GPIs in seven regions. The size of each box is defined as follows: (10-20°N, 67-75°E) for the AS, (5-15°N, 80-95°E) for the BoB, (5-20°N, 130-150°E) for the WNP, (10-20°N, 240-260°E) for the ENP, (10-20°N, 310-340°E) for the NATL, (10-25°S, 55-100°E) for the SIO and (10-25°S, 160°E -170°W) for the SWP. As shown in Fig. 2, the GPI index well captures the annual cycle pattern in all regions, especially the double peaks in the BoB.

Figure 2 shows that GPI represents well the combined effect of the four large-scale environmental processes on the cyclone genesis. A methodology was developed to quantitatively assess the relative contributions of four environmental parameters. Different from a conventional view that the seasonal change of vertical shear causes the bimodal feature, we found that the strengthened vertical shear alone from boreal spring to summer cannot overcome the relative humidity effect. It is the combined vertical shear, vorticity and SST that leads to the GPI minimum in boreal summer. It is noted that TC frequency in October-November is higher than that in April-May, which is primarily attributed to the difference of mean relative humidity between the two periods. In contrast, more super cyclones (Category 4 or above) occur in April-May than in October-November. It is argued that greater ocean heat content, the first branch of northward propagating intra-seasonal oscillations (ISOs) associated with the monsoon onset over the BoB, and stronger ISO intensity in April-May are favorable environmental conditions for cyclone intensification.

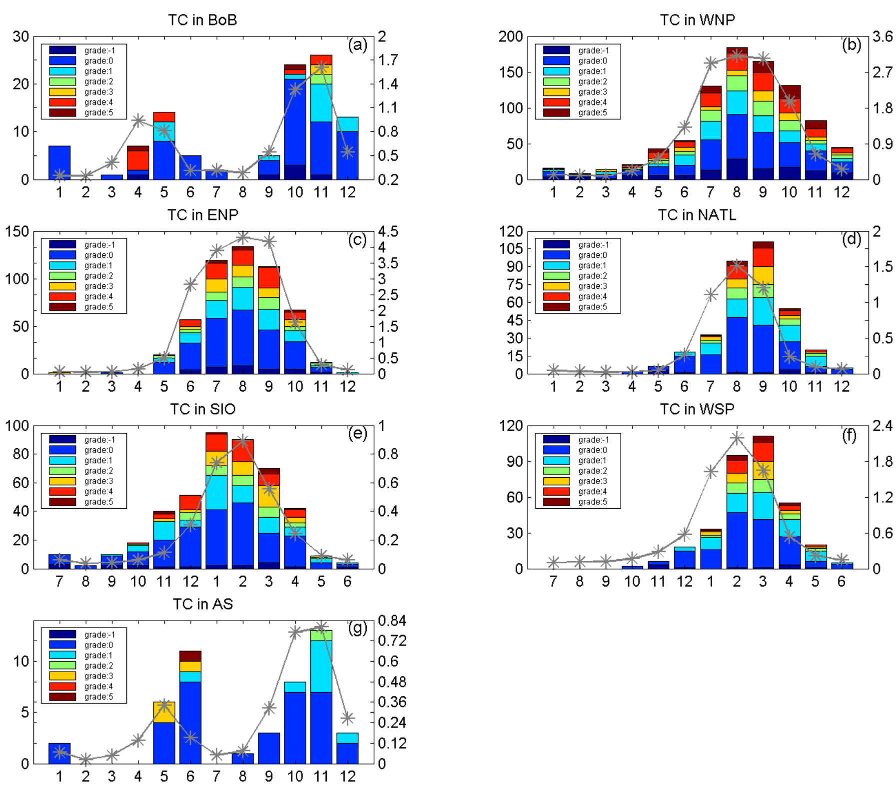

Fig. 2 Monthly TC numbers (column) during 1981-2009 in the (a) BoB, (b) WNP, (c) ENP, (d) NATL, (e) SIO and (f) WSP, respectively. According to Saffir-Simpson scale, grades -1 and 0 denote tropical depression and tropical storm, and grade 1 to 5 represents different typhoon strength, ranged from category 1 to category 5, as the legend shows. The overlaid gray curves represent the climatologic monthly GPI values. The left vertical-axis is for TC number and the right vertical-axis is for the GPI value.

3. Interannual Variation of Multiple Tropical Cyclone Events in the Western Pacific

The interannual variability of occurrence of multiple tropical cyclone (MTC) events during June-October in the western North Pacific is examined for the period of 1979-2006. It is found that the number of the MTC events is ranged from 2 to 9 per year, exhibiting a remarkable year-to-year variation. Seven active and seven inactive MTC years are identified. Compared to the inactive years, TC genesis locations are extended further to the east and in the meridional direction during the active MTC years. A composite analysis shows that the MTC inactive years are often associated with the El Niño decaying phase, as warm SST anomalies in the equatorial eastern-central Pacific in the preceding winter transition into cold SST anomalies in the concurrent summer. Associated with the SST evolution are suppressed low-level cyclonic vorticity and weakened convection in the WNP monsoon region.

In addition to the mean flow difference, significant differences between the active and inactive MTC years are also found in the strength of the atmospheric intraseasonal oscillation (ISO). Compared to the inactive MTC years, ISO activity is greatly strengthened along the equator and in the WNP region during the active MTC years. Both westward and northward propagating ISO spectrums are strengthened during the MTC active years compared to those during the inactive years. The combined mean state and ISO activity changes may set up a favorable environmental condition for the generation of the MTC events.

4. Characteristics of tropical cyclone genesis in the western North Pacific during the developing and decaying phases of two types of El Niño

During the developing phase of central Pacific El Nino (CPEN), more frequent TC genesis over the northwest quadrant of the western North Pacific (WNP) is attributed to the horizontal shift of environmental vorticity field. Such a northwestward shift resembles the La Niña composite, even though factors that cause the shift differ (in the La Niña case the relative humidity effect is crucial). Greater reduction of TC frequency happened during the decaying phase of eastern Pacific El Nino than CPEN, due to the difference of the anomalous Philippine Sea anticyclone strength. The TC genesis also exhibits an upward (downward) trend over the northern (southern) part of the WNP, which is linked to regional circulation and SST changes.

IMPACT/APPLICATIONS

The investigation of dependence of TC genesis efficiency on initial vortex structure and large-scale factors that control TC genesis and the construction of the typhoon reanalysis product may improve our current understanding of cyclogenesis dynamics and promote a more skillful prediction of TC genesis and intensity change.

TRANSITIONS

Results from this study may lead to improvement of TC prediction in the NOGAPS and COAMPS models. The TC dynamic initialization scheme used in the typhoon reanalysis effort may be transitioned into a 6.4 project.

RELATED PROJECTS

This project is complimentary to the ONR funding entitled "Initialization of tropical cyclone structure for operational application" in which we applied TC dynamic initialization strategy to the Observation System Simulation Experiment (OSSE) in an idealized setting using the WRF model and real-case TC forecast during 2009-2010 using NRL COAMPS-TC model. Knowledge gained from this project will help improve the current operational model TC initialization.

PUBLICATIONS

The following are papers published in 2012 that are fully or partially supported by this ONR grant:

Gao, J., and T. Li, 2012: Interannual variation of multiple tropical cyclone events in the western north Pacific, *Advances Atmos. Sci.*, in press.

Ge, X., T. Li, and M. Peng, 2012: Tropical cyclone genesis efficiency: mid-level versus bottom vortex. *J. Tropical Meteorology*, in press.

Li, T., 2012: Synoptic and climatic aspects of tropical cyclogenesis in western North Pacific. in *Cyclones: Formation, triggers and control, edited by K. Oouchi and H. Fudevasu, Noval Science Publishers*, in press.

Li, Z., W. Yu, T. Li, V. S. N. Murty, and F. Tangang, 2012: Bimodal character of cyclone climatology in Bay of Bengal modulated by monsoon seasonal cycle, *J. Climate*, in press.

Manuscript submitted or in preparation

Chung, P.-H., and T. Li, Characteristics of tropical cyclone genesis in the western North Pacific during the developing and decaying phases of two types of El Niño, *J. Climate*, submitted.

Xu, Y.-M., T. Li, and M. S. Peng, Tropical Cyclogenesis in the Western North Pacific as Revealed by the 2008-2009 YOTC data, manuscript in preparation.